

**Energy Research and Development Division
FINAL PROJECT REPORT**

CO₂-BASED CLEANING OF COMMERCIAL TEXTILES

The World's First CO₂ Solution for Cleanroom Textiles

Prepared for: California Energy Commission
Prepared by: CO₂Nexus Inc.



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This project would not have been achievable without the steadfast commitment of the CO2Nexus team members. Their willingness to work whatever long hours necessary to achieve this project's goals is a testament to what a hardworking and dedicated team can achieve.

Lastly, CO2Nexus is forever grateful to the California Energy Commission for their financial contributions and persistent moral support of this project.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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CO₂-Based Cleaning of Commercial Textiles is the final report for the “CO₂ Cleaning and Sterilization of Commercial/Industrial Textiles” project PIR-10-017. The information from this project contributes to Energy Research and Development Division’s Industrial/Agricultural/Water End-Use Energy Efficiency Program.

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ABSTRACT

CO2Nexus developed and demonstrated the world's first carbon dioxide (CO₂)-based garment and textile cleaning solution for the cleanroom laundry sector. Aramark Cleanroom Services' Los Angeles laundry facility served as the demonstration location for this project. During this project CO2Nexus, and its partners, designed, built, installed, validated and operated a CO₂-based cleanroom garment cleaning machine. Adapting CO2Nexus' existing textile and garment cleaning equipment to operate in a cleanroom laundry presented two main challenges: re-engineering of equipment to accommodate barrier style washing and validating the cleaning processes to meet the industry's rigorous cleaning standards.

CO2Nexus' Tersus™ Cleanroom Solutions demonstrated improved operational efficiency (50 percent higher throughput efficiency), lower operational cost (50 percent lower operational expenses) and significant utility savings compared to traditional water-based cleaning methods employed in cleanroom laundries. An estimated \$335,000 in annual utility related expenses could be saved by Aramark's Los Angeles facility if CO₂-based garment cleaning fully replaced water-based washing.

If fully implemented in the United States' cleanroom room laundry facilities, CO₂-based cleaning systems could generate an estimated nationwide annual savings of 6.7 billion gallons of water, more than 6 million therms of natural gas and 80 million kWh of energy.

This project demonstrated that widespread adoption of CO2Nexus' Tersus™ Cleanroom Solutions is economically preferable and can substantially reduce the water, energy and natural gas consumption of cleanroom laundries. Beyond cleanroom laundries, these solutions can service multiple industrial laundry market segments, thereby amplifying their environmental and financial impact.

Keywords: Carbon dioxide (CO₂), carbon dioxide-based cleaning, Aramark, cleanroom, cleanroom laundry, cleanroom garments, validation, utility consumption

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EXECUTIVE SUMMARY

Introduction

Commercial and industrial laundries, especially those in the cleanroom laundry sector, are some of the largest users of water and power in California and challenged with high infrastructure and operational expenses. A cleanroom laundry is dedicated to washing garments and related apparel accessories worn in a cleanroom environment (pharmaceutical and biotechnology related manufacturing; semi-conductor, wafer and other sensitive electronics manufacturing; aerospace; medical devices; etc.). These laundries must process garments to exacting cleaning and disinfection standards using sizeable amounts of potable water to clean garments in multi-step, water intense cycles. Approximately 660 gallons of water is used per cycle or more than twice the water consumed in a standard single door industrial washing machine.

This industry has high capital and operating costs combined with significant impacts on water, energy, chemical waste and discarded uniforms. While the industry has implemented water efficiency measures, currently there are no substitute solvents developed that provide environmental, performance and cost benefits over using water.

Project Purpose

This project commercially demonstrated a carbon dioxide (CO₂)-based cleaning solution for garments and textiles from the microelectronics industry (cleanroom) as an alternative to water-based cleaning systems.

While laundering textiles using carbon dioxide as the primary solvent has been commercially available for years, this was the world's first application of liquid CO₂ garment cleaning in a cleanroom laundry. Several barriers were overcome including modifying equipment to address the logistics of laundering garments in a cleanroom and developing validated cleaning programs to deal with rigorous cleanroom laundry cleaning standards.

Project Results

CO₂Nexus successfully developed and implemented the world's first CO₂-based barrier style cleanroom laundry machine in a commercial setting. A barrier style laundry has a physical wall that separates the "clean" and "dirty" side of the machine. This innovative project demonstrated a solution with low environmental impact (eliminating water, eliminating waste water and reducing energy consumption) and low cost (operational and capital investment). Performance testing also validated cleaning programs that successfully addressed the barriers from various garments that are serviced in a cleanroom laundry.

With CO₂Nexus' Tersus™ cleanroom solutions, greater operational efficiency (50 percent higher throughput efficiency) and lower operation cost (50 percent less expensive to process) were achieved. Substantially less utilities were used, resulting in significant water, energy and natural gas savings for the end user and California ratepayers.

Project Benefits

This project demonstrated that widespread adoption of CO2Nexus' Tersus™ cleanroom system is economical and can substantially reduce the water, energy and natural gas consumption of cleanroom laundries compared to water-based laundry systems. Beyond cleanroom laundries, these solutions can service multiple other industrial laundry market segments (such as police, military and niche garment markets), reducing the environmental and financial impacts.

Based on the project measurement and verification efforts, if Aramark's Los Angeles facility replaced all of their existing water-based washers with this new system an estimated \$334,620 could be saved annually in utility related expenses, including water and energy (60 million gallons of water, 55,200 therms of natural gas and 732,000 kWh). The Tersus™ cleanroom system cuts the costs about 50 percent on a per pound basis compared to water based textile cleaning methods. If all fourteen Aramark cleanroom laundry facilities implemented CO₂ laundry solutions, 840 million of gallons of water, 772,800 therms of natural gas and more than 10 million kWh of energy could be saved across the country annually¹.

If the entire cleanroom laundry industry in the United States adopted CO₂-based cleaning systems, an estimated nationwide potential annual savings of 6.7 billion gallons of water, more than 6 million therms of natural gas and 80 million kWh of energy could occur.

¹ Assuming each laundry facility has equal or similar annual garment volume.

CHAPTER 1:

Introduction

1.1 Purpose & Focus Area

This project introduced carbon dioxide (CO₂) textile cleaning into a commercial and industrial laundry setting, which has demanding cleaning requirements and which uses water as the primary cleaning solvent. Implementing this technology saves substantial energy, water and waste water and benefits public health and quality of life.

The cleanroom garment laundry industry was targeted since they are large consumers of water and energy, and producers of waste water. A water-based cleanroom laundry requires significant infrastructure, primary cleaning equipment and auxiliary equipment to achieve the demanding levels of cleanliness cleanroom garments require. Removing water as the primary cleaning solvent of cleanroom laundries is a game changing opportunity.

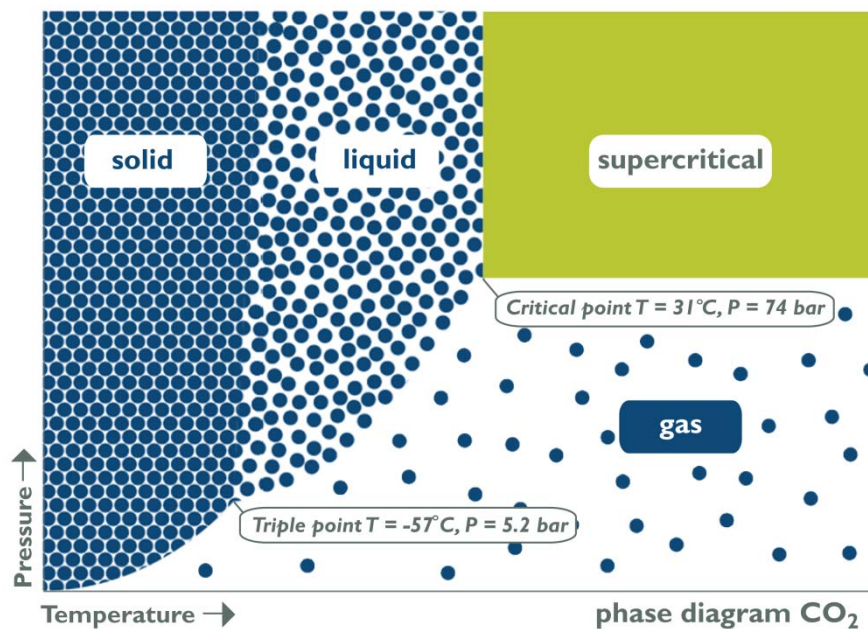
1.2 Introduction to Carbon Dioxide

Carbon dioxide is a naturally occurring and abundant gas that has excellent solvency properties when it becomes a liquid or a supercritical fluid. In addition to cleaning well, CO₂ leaves no secondary waste. The CO₂ used is the same gas that is used, for example, in beverage fizz at every local restaurant with a soda dispenser. No new CO₂ is generated or added to the atmosphere by the CO₂-based textile cleaning equipment. In fact, the CO₂ used during operation is waste or byproduct carbon dioxide generated by industrial facilities. It is non-hazardous, non-mutagenic, non-flammable, non-toxic, and non-ozone depleting. Due to its excellent cleaning properties and environmental and health aspects, CO₂ is used across multiple industries including pharmaceuticals, food manufacturing, de-contamination and sterilization.

CO₂ can exist in solid (dry ice), gaseous, liquid or supercritical states depending on the temperature and pressure conditions present. Solvency properties which are important for garment cleaning include:

- Low viscosity and surface tension, resulting in small pore penetration
- High density, resulting in strong solvent properties

Figure 1: Carbon Dioxide Phase Diagram



Source: CO2Nexus Inc.

1.3 Product Demand & Potential Impact

Water scarcity and depletion is a serious problem across the United States, particularly in the West. Commercial / industrial laundry has long been one of the major water consumers and uses billions of gallons of potable water each year. While the industry has implemented water efficiency measures, there have been no outright substitute solvents that offer environmental, performance and cost benefits over water – until now.

Water use also correlates with energy intensity. After water-based washing, garments must be dried to remove the remaining water, which requires energy. With water and energy sources dwindling, it's no surprise state and federal legislators have been demanding utility conservation from the public and private businesses for some time.

The benefits of implementing CO₂ textile cleaning at end users throughout California are significant, including:

- Preserving scarce water sources
- Reducing textile cleaning related wastewater/sewage
- Reducing energy demand

CHAPTER 2:

Methodology

2.1 Technology Status

Carbon dioxide has been commercially used to clean garments – primarily consumer dry cleaning garments – for about a decade. CO2Nexus and partners have been developing new applications of CO₂-based textile cleaning since 2008. CO2Nexus maintains intellectual property and know-how in the cleaning of numerous garment types and industrial textiles. CO2Nexus offers Tersus™ Cleaning Solutions – a universal cleaning system for industrial laundry services, commercial and retail dry cleaners, uniform cleaning providers, uniform based institutions (hotels, casinos, corrections facilities, military, etc.), as well as various niche processing applications (for example oil & gas industry, coating protected garments).

Figure 2: Tersus™ AA-40-00



Source: CO2Nexus Inc.

The cleaning cycle can be summarized as follows: Gaseous CO₂ is introduced into the cleaning chamber and pressurized into liquid form (about 700 psi and 60 °F). Garments go through a cleaning cycle, after which the chamber is de-pressurized, thereby returning the CO₂ to a gaseous form and leaving the garments dry and cool to the touch. Unlike conventional water based cleaning, no heat to dry clothes is used which results in longer lasting fabrics and significantly faster cycle times. All of the CO₂ is circulated through a filter to remove particulates, distilled (to remove impurities like body oils and other extraneous items) and returned for re-use. The only waste stream is the oils and additives that are extracted via distillation, which can be (and are) recycled for other uses, such as in bio-diesel blends (application specific).

Benefits of CO₂-based textile cleaning include:

- Environmentally sustainable – no chemicals, no water, no hazardous secondary waste stream
- No heat – garments last longer and retain their functionality
- Faster cycle time
- Only 1 machine needed for wash + dry (+ bioburden reduction)
- Reduced utility bills – water, electricity, natural gas, waste stream remediation
- Streamlined operations – simplified workflow, shorter processing time, less labor needed
- Overall lower operation costs

With this project CO₂Nexus endeavored to develop a CO₂-based solution for the cleanroom laundry market – a goal never previously attempted by anyone in the CO₂ technology field and beyond. Cleanroom laundries, being quite different from your average textile laundry facility, possess their own set of challenges CO₂Nexus had to overcome.

2.2 Cleanroom Laundries

A cleanroom laundry is a laundry dedicated to washing garments and related apparel accessories worn in a cleanroom environment (pharmaceutical and biotechnology related manufacturing; semi-conductor, wafer and other sensitive electronics manufacturing; aerospace; medical devices; etc.). Cleanroom laundries are bound to strict cleaning standards and rigorous quality control mechanisms. Highly trained staff monitors these control mechanisms as part of an ongoing quality assurance system.

Due to the unique and highly technical cleaning requirements for cleanroom apparel a number of accessory equipment systems are also required beyond standard washers and dryers, such as deionized water and reverse osmosis systems, chemical detergent injection system and HEPA air filter system – resulting in high equipment, operation and maintenance costs.

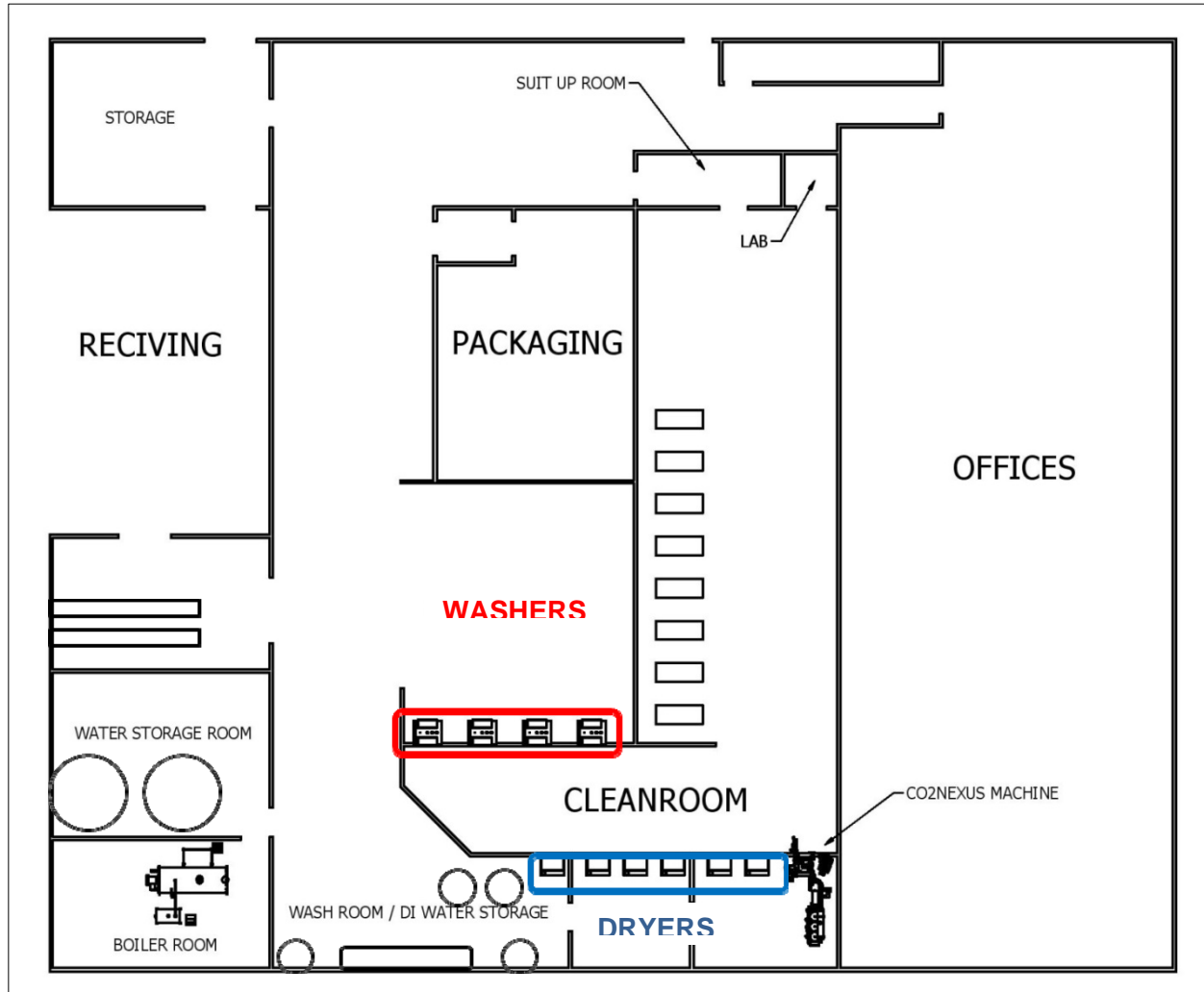
Because cleanroom garments must maintain their strict levels of cleanliness after washing, garments are dried, folded and processed inside a cleanroom. The washing machines in a cleanroom laundry straddle the cleanroom wall and have two doors. Garments enter on the outside of the cleanroom into one door of the machine (e.g. dirty side) and exit the washing machine through a second door into the cleanroom (e.g. clean side). This is called a barrier style system.

During washing vast amounts of potable water are used to clean garments in multi-step, water intense cycles. Approximately 660 gallons of water is used per cycle by the standard water-based cleanroom washing machine (that's more than twice the water consumed in a standard single door industrial washing machine). Roughly 610 gallons of detergent infused waste water

is released each cycle back into the local sewer system. After washing garments are dried in industrial air-regulated dryers, resulting in substantial energy usage.

Figure 3: Aramark Cleanroom Services (Los Angeles, CA) Facility Layout

Source: CO2Nexus Inc.



2.3 Challenges

The challenges of adapting CO2Nexus' existing textile cleaning equipment and know-how to service a cleanroom laundry were two-fold:

- **Equipment:** Conventional CO₂ textile cleaning equipment is similar to a standard washing machine, in that it has one door garments enter and exit out of. CO2Nexus was required to re-design a model which has two doors, allowing for garments to enter on the “dirty” side (e.g. outside a cleanroom) and exit on a “clean” side (e.g. into a cleanroom). Design elements accounting for the rigorous cleaning standards, such as filtration, also needed to be considered.

- Process: While carbon dioxide has a significant history being an effective cleaning and disinfection method, in order to operate in a cleanroom laundry, cleaning performance must be validated via a thorough certification process. CO2Nexus would need to go through a process development cycle, to ensure cleaning standards are consistently met.

2.4 Goals & Objectives

- Develop and demonstrate the world's first CO₂-based barrier style cleanroom laundry machine.
- Develop and demonstrate validated cleaning programs to address the various garment types and styles serviced in a cleanroom laundry.
- Demonstrate operational efficiency and lower operational costs for end-users (e.g. cleanroom laundry service providers).
- Demonstrate reduced utility usage:
 - Eliminate water use
 - Eliminate waste water
 - Reduce energy consumption

CHAPTER 3: Activities

Project activities commenced in January 2011 and continued through December 2013. The following is a summary of activities as determined by the project's scope of work.

3.1 Demonstration Partner

At the start of the project Aramark Cleanroom Services was secured as the demonstration partner. Aramark operates 14 cleanroom laundry facilities across the United States and Puerto Rico, including an operation in Los Angeles. The Los Angeles facility served as an ideal demonstration model – they service a variety of clientele with different cleaning challenges (pharmaceuticals and microelectronics); they utilize all possible operable space available and could not increase their throughput capacity without adopting novel, space saving laundry systems; and they operate in the heart of high water and power prices on the already stressed grid of the greater Los Angeles area. Aramark was quickly receptive to the goals and potential impact this project could have on both their Los Angeles facility and their other operations in the future.

Figure 4: Aramark Logo



Source: Aramark Cleanroom Services

3.2 Benchmarking

The goal of this task was to determine the operating conditions, including cleaning procedures, cleaning performance, labor, material workflow and utility consumption at Aramark's Los Angeles cleanroom laundry facility. Data was collected over a period of several months. Upon conclusion of this task it was re-affirmed that CO₂ cleaning solutions would bring great benefits to such facilities: significantly reduce the required infrastructure and equipment, improve throughput, reduce utility usage and reduce operations costs.

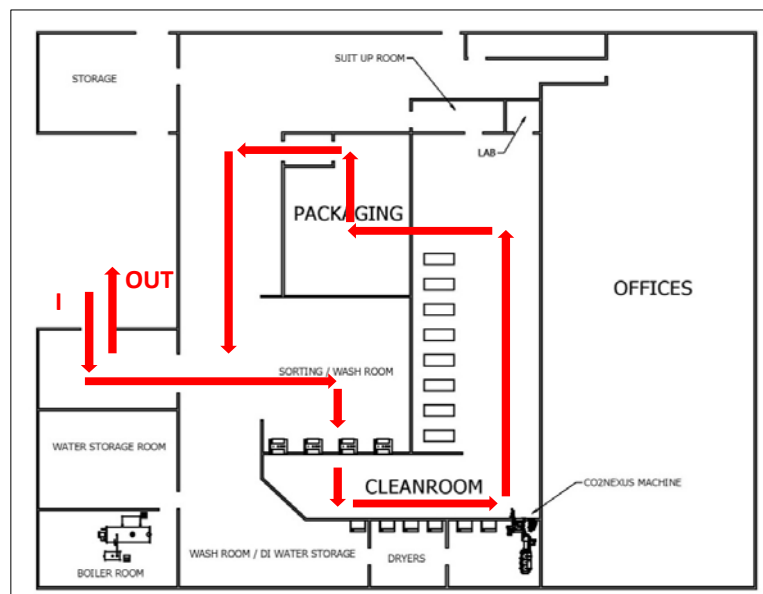
3.2.1 Operations

A water-based cleanroom laundry requires significant infrastructure, primary cleaning equipment and auxiliary equipment to operate. In Aramark's Los Angeles facility, this includes:

- Washer-extractors: Three barrier style washers, each with 330 lb garment capacity per cycle. 660 gallons of potable water used per cycle.
- Chemical injection system: Delivers detergent and other cleaning chemicals to washers.
- Dryers: Seven steam dryers with HEPA air filter systems, each with 90-110 lb capacity.
- Reverse Osmosis (RO) / Deionized Water (DI) Systems: Used to transform tap water to filtered water suitable to wash cleanroom garments. For every gallon of water that is conditioned there is a gallon of water that is wasted down the drain.
- Boiler (150 horsepower): Heats water for wash cycle and creates steam for dryers.
- Auxiliary washers: Additional washers for specialty garments and accessories (goggles, mops, floor mats, etc).
- Waste water holding tanks: Underground holding tanks to collect waste water before it enters sewer system.

Processing garments as quickly and as efficiently as possible is paramount to Aramark maintaining its rigorous, fast paced and high quality service. After garments arrive on site, their barcode is scanned, they are sorted for washing, washed, dried, inspected for damages, sorted and folded, packaged and either returned to the customer or sent out for irradiation. Garments requiring full sterilization are shipped to an external party to undergo irradiation.

Figure 5: Path of Garments Through Los Angeles Facility



Source: CO2Nexus Inc., Aramark Cleanroom Services

Aramark services a variety of garments, including coveralls, scrubs and frocks, and other accessories such as goggles and boots. Garments are typically made from polyester or polyester – carbon fiber blends. The presence of carbon fiber helps reduce the presence and creation of static electricity on garments.

3.2.2 Quality Control & Cleaning Standards

To maintain process quality any cleanroom laundry, including Aramark’s Los Angeles facility, must implement rigorous quality control protocols. Aramark facilities are ISO 9001:2008 certified – an international standard for quality management systems. All equipment, wash processes, garment handling, and environmental conditions are dictated by strict standard operating procedures (SOPs). Garment regularly undergo quality assurance testing to insure standards are maintained. Four characteristics are used to measure garment quality. Any new wash process, like CO₂-based cleaning, must meet validation testing to achieve these standards.

Table 1: Garment Quality Assurance Standards

Characteristic	Importance	Test Method	Description	Allowable Limit (Industry standard)
Particles	Cleanrooms are classified based on particles present in the air. Control of particles present on garments is key to maintaining overall cleanroom integrity.	ASTM-F51	Measures nonviable particulates	<1000 particles >5 µm per ft ²
		Helmke Drum	Measures submicron particles	<1200 particles >5 µm per ft per minute shedding
Electrostatic Discharge (ESD)	Static charge control is critical in the cleanrooms of many manufacturing industries, such as electronics, aerospace and semiconductor.	ESD STM 2.1	Measures surface resistivity and surface resistance of fabric	1.0 x 10 ⁵ – 1.0 x 10 ¹¹ ohms
Ionic Residue	Controlling the ionic contamination of garments is particularly important in the semi-conductor and microelectronics industry.	ASTM Ion Chromatography	Measures matter that is not electrically neutral but either negatively or positively charged	Each matter type has own ppm limits.
Microbiological Activity / Bioburden	In industries like pharmaceuticals and biotechnology, production processes are extremely sensitive to biological contamination.	Sterility testing in accordance with ANSI/AAMI/ISO 11137-2006	Measures presence of microbiological life	Activity present in standard sample determines level of radiation required to achieve desired sterility level.

Source: CO2Nexus Inc.

3.2.3 Economy

Economy of a cleanroom laundry is measured in cost per pound of garments. Utility consumption, chemical usage, labor, auxiliary equipment contracts and throughput all combine to create a matrix of costs that determines the cost per pound of processed garments.

Table 2: Cost Per Pound Using Water-Based Systems at Los Angeles Facility (utility only)

Specification	Cost (\$ per lb)
Water (Golden State Water Company)	\$ 0.088 per lb
Reverse Osmosis / Deionized Water (equipment contract)	\$ 0.015 per lb
Gas (SCGC)	\$ 0.028 per lb
Electric (SCE)	\$ 0.054 per lb
TOTAL cost per pound to process	\$ 0.212

Source: CO2Nexus Inc.

3.3 Design & Engineering

Design and engineering took place from January through April 2011. Together with partners, Czero Inc.² and FeyeCon Development & Implementation BV³, CO2Nexus undertook the task of modifying the Tersus™ single door design (see Figure 2) to a barrier system suitable for a cleanroom laundry. Several significant changes were developed:

- Drive system: The cleaning basket in a CO₂ garment cleaning machine rotates just as in a traditional water washing machine. The cleaning basket in the Tersus™ AA-40-00 (single door) operates with a traditional drive shaft set up. A drive shaft is not suitable for a machine with doors at either end of the cleaning vessel. A hydraulic drive system was developed which engages the cleaning basket on either end and enables basket rotation. The hydraulic system affords high torque which enables optimum basket performance and cleaning action.
- Cleaning basket: The cleaning basket required a re-design as well to comply with a two door cleaning vessel. The interface between the basket and how it engaged with the drive system was a main focus.

² Czero is a mechanical engineering services firm focused on sustainable industrial design.

³ FeyeCon is a CO₂ technology development enterprise.

- Filter system: To maximize particulate removal (key to achieving the rigorous cleanroom garment cleaning standards) the Tersus™ filter system was improved. Several design iterations were developed and tested before arriving at an easy to maintain (full disassembly possible) design with multiple filter stages.
- Heat exchanger: The efficient circulation of carbon dioxide and distillation of impurities pulled from garments is vital to maintaining an effective CO₂ textile cleaning machine. Modifications to the Tersus™ heat exchange system were implemented to improve such efficiency.

3.4 Fabrication & Assembly

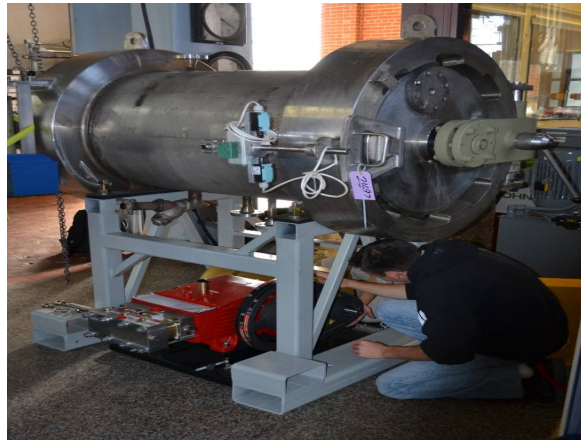
After extensive vendor vetting and parts acquisition, construction of the equipment began in September 2011. By May 2012 the machine was fully assembled and had passed various mechanical and functional testing protocols established by CO₂Nexus. The machine was assembled by the CO₂Nexus team members in Fort Collins, CO at the Engines and Energy Conversion Lab. This lab focuses on fostering novel sustainable technologies and is part of Colorado State University. The below photos illustrate progress of the assembly process.

Figures 6 & 7: Early Stages Assembly, September 2011



Source: CO₂Nexus Inc.

Figures 8 & 9: Mid-stage Assembly, October/November 2011



Source:

CO2Nexus Inc.

Figures 10 & 11: Final Assembly Stage, January 2012



Source: CO2Nexus Inc.

Prior to the machine being shipped to Aramark's facility in Los Angeles multiple rounds of quality control testing occurred using Aramark garments to determine an initial cleaning baseline.

Figures 12, 13 & 14: Control Testing Prior to Installation, March 2012



Source: CO2Nexus Inc.

3.5 Installation & Commissioning

Pre-installation preparations took place at Aramark from May through August 2012, which included: installation of an onsite CO₂ tank, rearranging of existing equipment, reconstruction of cleanroom wall to accommodate new CO₂ garment cleaning machine (Tersus™ BA – barrier system), reinforcement of floor to accommodate weight of Tersus™ BA machine, and other minor building upgrades.

Tersus™ BA was shipped to Los Angeles in August 2012. Set-up, start-up and commissioning took place through October 2012.

Figures 15 & 16: Installation Begins in Los Angeles, August 2012



Source: CO2Nexus Inc.

Figures 17, 18 & 19: Installation Complete, September 2012



Source: CO2Nexus Inc.

CO2Nexus hosted several training and demonstration sessions in September and October 2012. A multi-day owner/operator training course was held which covered: safety, basic machine component understanding, introduction to operation and equipment maintenance. Operations & Maintenance manuals were provided to Aramark staff.

The machine was operated for several weeks under extreme operating conditions to test reliability and robustness. No major mechanical failures were incurred and the Tersus™ BA system proved itself mechanically reliable.

All of these activities (training, manuals, and demonstration of machine reliability) along with the satisfaction of additional materials and infrastructure related requirements comprise Aramark's Installation Qualifications. All equipment parts and any additives used (oils) for equipment operation needed to be inspected and approved for use. The infrastructure surrounding the machine, with a strong emphasis on the machine's interaction with the barrier wall of the cleanroom, was built to Aramark's qualification requirements and approved after completion. All activities related to installation qualification were completed by January 2013.

Parallel to installation qualification testing, process optimization continued. Process optimization is the modification of cycle parameters to achieve the best possible efficiency and cleaning performance per cycle. Parameters modified include pressure, temperature and time of each wash and rinse cleaning step. Building on the initial cleaning performance test results

obtained prior to installation, CO2Nexus endeavored to improve cleaning performance in preparation for undergoing Aramark's Operational Qualification testing protocol.

Figures 20, 21 & 22: Process Optimization Testing, November 2012



Source: CO2Nexus Inc.

3.6 Operational Validation & Operations

Due to the rigorous cleaning demands of cleanroom garments, strict quality assurance protocols are in place to ensure those demands are consistently met. Any new technology must undergo operational validation to prove its cleaning performance capabilities and consistency. The validation process is a meticulous process involving many series of batch testing of garments, modifications, if necessary, to the cleaning process, followed by more batch testing of garments. As CO₂-based garment cleaning is entirely new to the cleanroom laundry industry, a lengthy and thorough validation protocol was required. CO2Nexus carried out validation testing for approximately 10 months beginning in December 2012. A summary of Operational Validation results is found in section 4.1.2 *Cleaning Performance*.

Cleaning performance is validated by measuring the four characteristics described in *Table 1: Garment quality assurance standards*: particles, electrostatic discharge (ESD), ionic residue and bioburden. Particle count and ESD are measured in-house at Aramark's quality assurance testing department. Ionic residue and bioburden are measured at third parties – TEI Analytical and SteriPro Labs respectively.

Tersus™ BA cleanroom system achieved high marks in cleaning performance – in some cases outperforming water-based washing method. A full analysis of results from validation testing is found in section 4 *Results*.

During operations CO₂-based detergent, developed by CO2Nexus, was successfully introduced into the system. The machine underwent regular scheduled maintenance, as well as some upgrades, including improvements to the filter and drive systems, programming updates and online remote access establishment.

In addition to cleaning performance improvement, both cycle time and volume per cycle were optimized during the operational period.

Table 3: Tersus™ BA Cycle Time Improvement

Cycle Time – CO2 Process (dry to dry, minutes)		
Start of Operations	End of Process Optimization	Progress
35-45 min	24-25 min	Reduced cycle time by 44%

Source: CO2Nexus Inc.

Table 4: Tersus™ BA Throughout Improvement

Wash Volume – CO2 Process (pounds)		
Start of Operations	End of Process Optimization	Progress
20 lbs	30 lbs	Increased volume by 50%

Source: CO2Nexus Inc.

3.7 Measurement & Validation

Parallel to operations, data was collected documenting the utility performance of the Tersus™ BA cleanroom system. Throughout 2012 data was collected via Aramark from various utility providers, including Golden State Water Company, Southern California Edison and Southern California Gas Company. In November 2012 a measurement and verification report demonstrating substantial operational cost and utility consumption savings was submitted. Full analysis can be found in section 4 *Results*.

3.8 Production Planning

In the final two months of 2012 CO2Nexus evaluated the next steps required to commercially launch the Tersus™ BA cleanroom system. Evaluation conclusions are found in section 6 *Next Steps*.

CHAPTER 4:

Results

4.1 CO₂ versus H₂O Cleanroom Garment Laundering

4.1.1 Cycle time & Throughput

Because garments are already dry when a CO₂ wash cycle is complete, cycle time is inherently shorter. Removing the drying step improves operational efficiency and reduces dry-to-dry cycle time by 75percent.

Table 5: Cycle Time, H₂O vs. CO₂

Cycle Time – H ₂ O vs. CO ₂ (dry to dry, minutes)		
H ₂ O	CO ₂	Progress
80-100 min	24-25 min	Reduced cycle time by 75%

Source: CO₂Nexus Inc.

Shorter cycle time translates to increased daily throughput and ultimately more profit for the end user. Even though the volume of the Tersus™ BA demonstration machine is only 30 lbs, it still outperforms water methods in terms of throughput nearly 2 to 1.

Table 6: Throughput, H2O vs. CO2

Throughput – H2O vs. CO2 (dry to dry)	
H ₂ O	CO ₂
3.3 lbs per minute	6 lbs per minute

Source: CO2Nexus Inc.

4.1.2 Cleaning Performance

For approximately ten months, testing (as part of Operational Qualification) was performed on all garment types in Aramark's catalog⁴, with the exception of boots and goggles⁵. *Table 7 (A & B)* provides a summary of cleaning performance results. Results are measured and validated by Aramark's in-house quality assurance department and third party testing facilities.

Table 7 A: Operational Validation Cleaning Performance Summary

Characteristic	Importance	Test Method	Description	Allowable Limit	CO ₂ Process
Particles	Cleanrooms are classified based on particles present in the air. Control of particles present on garments is key to maintaining overall cleanroom integrity.	ASTM-F51	Measures nonviable particulates	<1000 particles >5 µm per ft ²	PASS
		Helmke Drum	Measures submicron particles	<1200 particles >5 µm per ft per minute shedding	PASS
Electrostatic Discharge (ESD)	Static charge control is critical in the cleanrooms of many manufacturing industries, such as electronics, aerospace and semiconductor.	ESD STM 2.1	Measures surface resistivity and surface resistance of fabric	1.0 x 10 ⁵ – 1.0 x 10 ¹¹ ohms	PASS

Source: CO2Nexus Inc.

⁴ Coveralls, scrubs, frocks, hoods; various fabric types.

⁵ Preliminary process testing was completed on both boots and goggles. Initial cleaning results were positive; however additional process modifications are required for full validation to occur. Developing said optimizations requires time and budget beyond what is available in this grant project. CO2Nexus and Aramark will endeavor to develop CO₂-based boot and goggle cleaning applications in the future.

Table 7 B: Operational *Validation* Cleaning Performance Summary

Characteristic	Importance	Test Method	Description	Allowable Limit	CO ₂ Process
Ionic Residue	Controlling the ionic contamination of garments is particularly important in the semi-conductor and microelectronics industry.	ASTM Ion Chromatography	Measures matter that is not electrically neutral but either negatively or positively charged	pH 5.5-6.5	PASS
				Cl 10 ppm	PASS
				Sulfate 15 ppm	PASS
				CaCO ₃ 10 ppm	PASS
				Arsenic 0.5 ppm	PASS
				Li 0.15 ppm	PASS
				K 5 ppm	PASS
				Si <2.0 ppm	PASS
				Na 5 ppm	PASS
Bioburden	In industries like pharmaceuticals and biotechnology, production processes are extremely sensitive to biological contamination.	Sterility testing in accordance with ANSI/AAMI/ISO 11137-2006	Measures presence of microbiological life: aerobes, spore formers, Fungi/Yeast/Mold	1200 CFU	PASS / ON-GOING

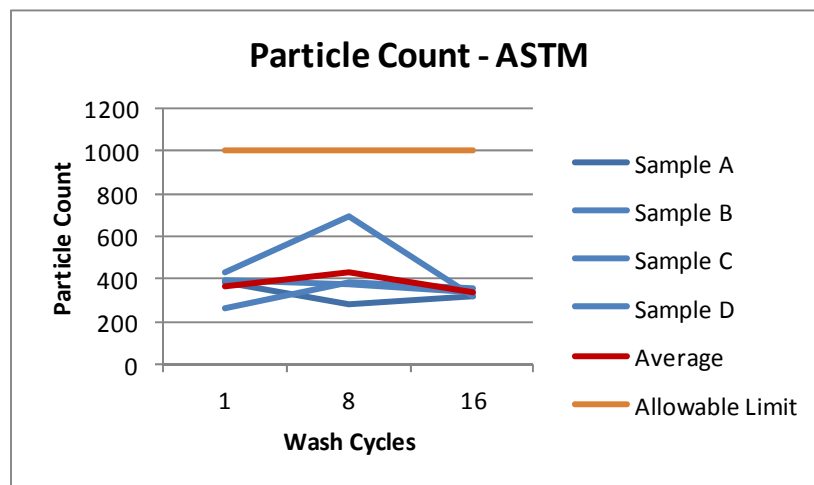
Source: CO2Nexus Inc.

This is the culmination of hundreds of cycles of testing. In the event garments did not meet the targeted cleaning performance standard, process modifications were implemented. Process modifications included: wash and rinse times, pressure, temperature and detergent.

To document garment longevity and possible wear, samples were tested after one cycle, eight cycles and sixteen cycles during a testing period.

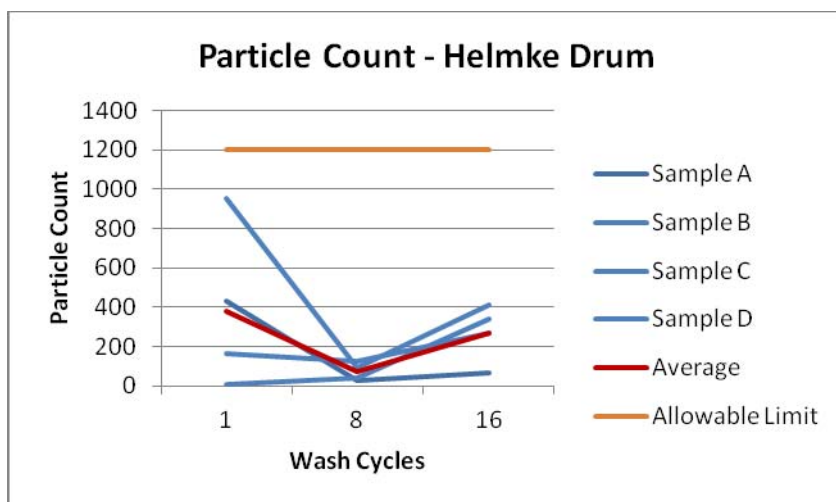
A sample segment of data is provided below.

Figure 23: Particle Count as Measured by ASTM



Source: CO2Nexus Inc.

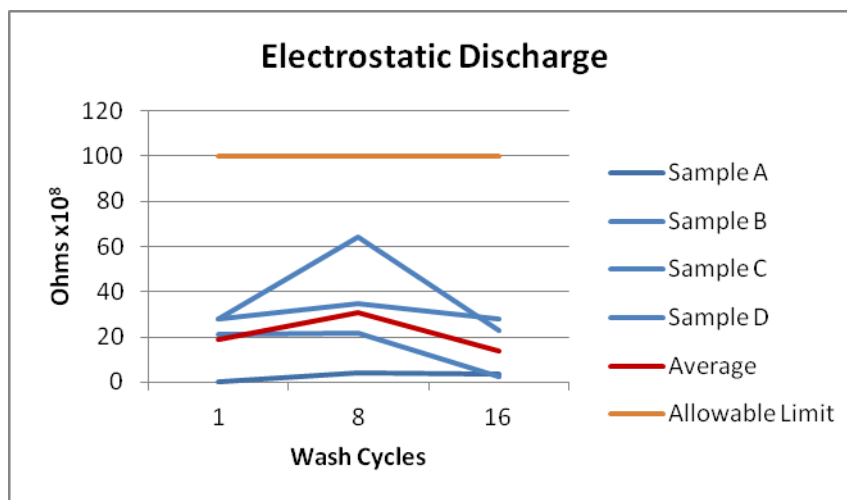
Figure 24: Particle Count as Measured by Helmke Drum



Source: CO2Nexus Inc.

Tersus™ BA cleanroom solutions scored consistently below the maximum allowable limit of particles. On average water-based textile cleaning results in particle counts around 500. The CO₂ process scored regularly below 500, indicating CO₂ textile cleaning removes particles more efficiently than water-based cleaning.

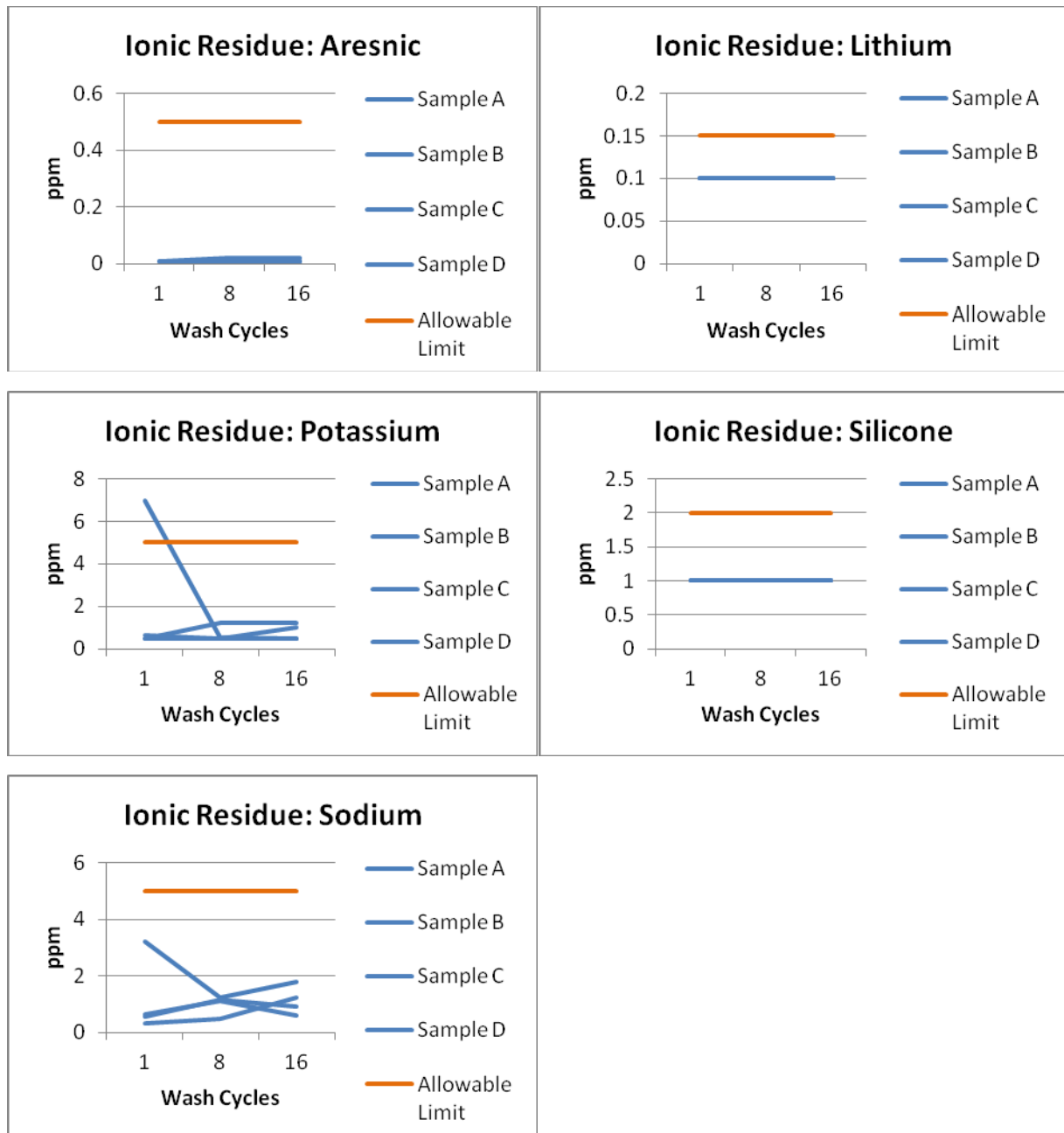
Figure 25: Electrostatic Discharge Measurement



Source: CO2Nexus Inc.

Initial processing resulted in some ESD spikes, however after optimization efforts solutions scored consistently within the allowable ESD range.

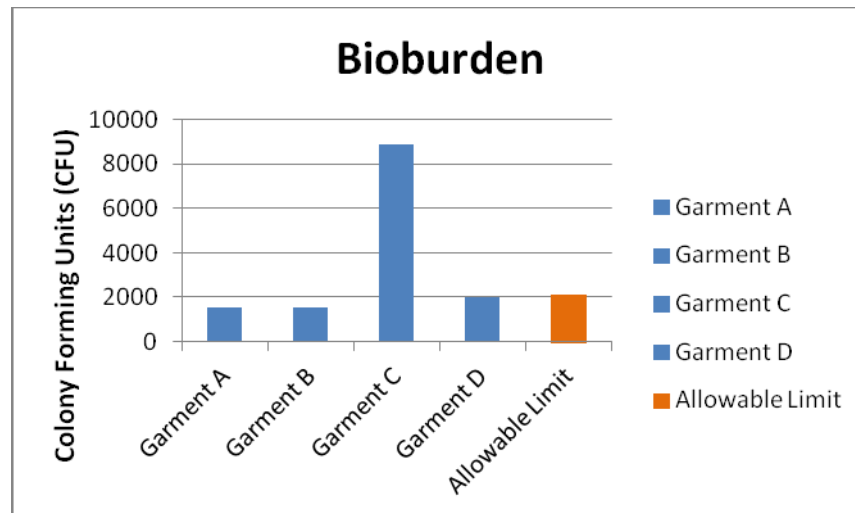
Figure 26: Ionic Residue Measurements



Source: CO2Nexus Inc.

On average Tersus™ BA cleanroom solutions **meet ionic residue thresholds** and therefore passes ionic residue validation.

Figure 27: Bioburden Measurements



Source: CO2Nexus Inc.

Initial rounds of bioburden testing yielded, on average, data that met Aramark standards, however a few garment samples presented colony forming units (CFU) values higher than 2100 CFU (maximum allowable limit). For example, in the above data set garment C does not pass. Because some industries, such as pharmaceuticals and biotechnology, are extremely sensitive to biological contamination, Aramark asked that we continue our process optimization efforts in this area. The goal is for every single garment to achieve bioburden levels below 2100 CFU. Beyond the scope of this project CO2Nexus will continue to improve its cleaning performance on this topic.

4.2 Operational & Utility Performance

Economy of a cleanroom laundry is measured in cost per pound of garments. Utility consumption plays a large role in economy calculations.

Table 8: Aramark's Water-Based Process Costs

Aramark Water-Based Wash / Dry Process Costs (utility only)	
Specification	Cost (\$ per lb)
Water (Golden State Water Company)	\$ 0.088
Reverse Osmosis / Deionized Water (equipment contract)	\$ 0.015
Gas (SCGC)	\$ 0.028
Electric (SCE)	\$ 0.054
Chemical usage (Ecolab)	\$ 0.027
TOTAL cost per pound to process with Water	\$ 0.21 per lb

Source: CO2Nexus Inc.

Table 9: CO2Nexus' CO2-Based Process Costs

Tersus™ Cleanroom Solution Process Costs (utility only)	
Specification	Cost (\$ per lb)
Carbon Dioxide (Linde Gas)	\$ 0.024
Gas (SCGC)	\$ 0.020
Electric (SCE)	\$ 0.029
Detergent (CO2Nexus)	\$ 0.040
TOTAL cost per pound to process with CO2	\$ 0.113 per lb

Source: CO2Nexus Inc.

Data reported for Tersus™ BA cleanroom systems are very conservative figures. Additional calculations reveal process costs have the potential to be **30 percent lower** than reported above.

Table 10: H2O vs. CO2 Process Utility Cost Comparison

Side by Side Utility Comparison			
H ₂ O		CO ₂	Difference
Cost (\$ per lb)	Specification	Cost (\$ per lb)	Cost (\$ per lb)
\$ 0.102	Water / RODI	---	- \$ 0.102
---	Carbon Dioxide	\$ 0.024	+ \$ 0.024
\$ 0.028	Gas	\$ 0.020	- \$ 0.008
\$ 0.054	Electric	\$ 0.029	- \$ 0.025
\$ 0.027	Chemical / Detergent	\$ 0.040	+ \$ 0.013
\$ 0.212 per lb	TOTAL cost per pound to process	\$ 0.113 per lb	\$ 0.099 per lb savings

Source: CO2Nexus Inc.

Operation costs for the Tersus™ BA cleanroom system are roughly **50% cheaper** on a per pound basis than water-based textile cleaning methods.

If Aramark's Los Angeles facility replaced all of their existing water-based washers with Tersus™ cleanroom systems an estimated \$334,620 could be saved annually in utility related expenses (water, natural gas and electricity).

Table 11: Long Term Operational Savings Potential, Aramark's Los Angeles Facility

Operation Cost Savings (Utility savings only, excl. labor & equipment related savings)	
Per lb savings	\$ 0.099
Per Week savings * (avg. 65,000 lbs processed per week)	\$ 6,435
Annual savings * (avg. 3,380,000 lbs processed annually)	\$ 334,620

Source: CO2Nexus Inc.

* These savings are specific to Aramark's Los Angeles cleanroom laundry. Garment volume determines potential weekly and annual savings and each laundry facility has its own unique volume.

Table 12: Annual Utility Savings, Aramark's Los Angeles Facility

Annual Utility Savings		
Utility	Cost Saving (per year)	Utility Usage Savings (per year)
Water	\$ 258,348	est. 60 Million gallons
Gas	\$ 27,040	est. 55,200 therms
Electric	\$ 84,500	est. 732,000 kWh

Source: CO2Nexus Inc.

Significant operation cost and utility savings can be achieved with the Tersus™ BA cleanroom solution. Because the solution is completely water free, the achievable water savings is paramount. An estimated 60 million gallons of water can be saved per year by one laundry facility. That's equivalent to the water used by 967 residential homes in California in one year⁶.

⁶ Based on 170 gallons per day used indoors in average California household as report by: DeOreo, W. & Mayer, P., "California Single Family Water Use Efficiency Study", California Department of Water Resources, Aquacraft Water Engineering & Management, April 11, 2011.

CHAPTER 5:

Analysis & Impact

5.1 Achieving Goals

At the start of this project CO2Nexus established a number of technical, financial and environmental related goals, all of which were achieved during this demonstration project.

CO2Nexus successfully developed and implemented the world's first CO₂-based barrier style cleanroom laundry machine in a commercial setting. Cleaning performance testing resulted in successfully validated cleaning programs able to address various garments serviced in a cleanroom laundry.

Greater operational efficiency (50 percent higher throughput efficiency) and lower operation cost (50 percent cheaper to process) were achieved using a CO₂-based garment cleaning system.

Substantially less utility usage was documented, resulting in significant water, electricity and natural gas savings for the end user and state of California.

CO2Nexus is confident they have demonstrated a technically viable industrial laundry solution that affords enormous utility related conservation.

5.2 Impact

The utility usage difference between water and CO₂-based cleanroom garment laundering is enormous. At Aramark's Los Angeles facility alone an annual utility savings of 60 million gallons of water, 55,200 therms of natural gas and 732,000 kWh of energy could be realized.

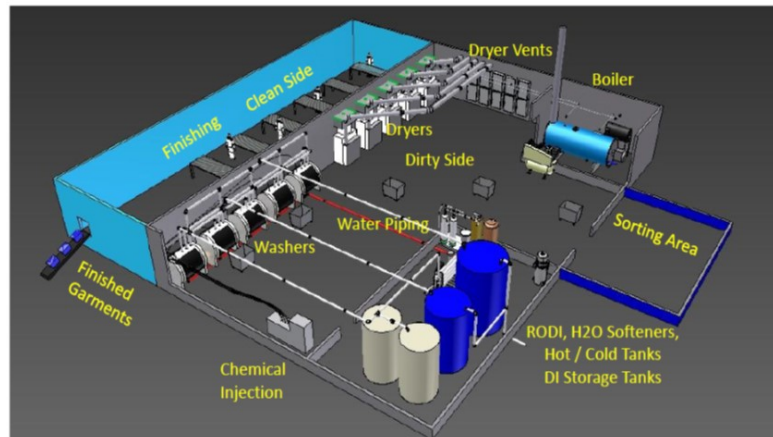
If all fourteen Aramark cleanroom laundry facilities implemented CO₂ laundry solutions, 840 million of gallons of water, 772,800 therms of natural gas and over 10 million kWh of energy could be saved across the country annually⁷.

If the entire cleanroom laundry industry in the United States adopted CO₂-based cleaning systems, we estimate a nationwide potential annual savings of 6.7 billion gallons of water, over 6 million therms of natural gas and 80 million kWh of energy.

Beyond the massive utility savings potential, CO₂-based barrier style cleanroom systems enables end users to establish barrier style laundries quickly and easily. Because the extensive primary and auxiliary equipment required for water-based laundries (dryers, DI / RO water filtration systems, underground waste water holding tanks, etc.) is not required, a CO₂-based laundry facility can be set up on a small footprint, with minimal infrastructure and lower capital investment.

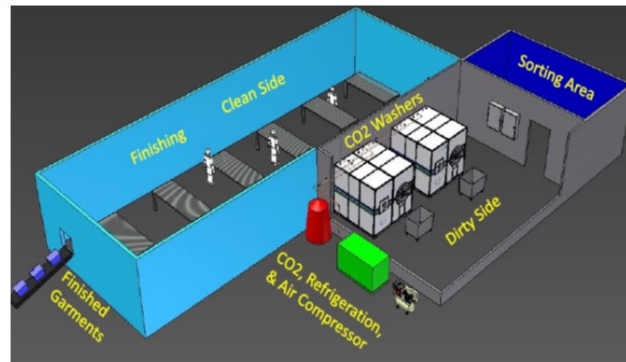
⁷ Assuming each laundry facility has equal or similar annual garment volume.

Figure 28: H2O-Based Cleanroom Laundry Model



Source: CO2Nexus Inc.

Figure 29: CO2-Based Cleanroom Laundry Model



Source: CO2Nexus Inc.

Table 13: H2O vs. CO2 Cleanroom Laundry Facilities

H ₂ O-Based Laundry	CO ₂ -Based Laundry
<ul style="list-style-type: none"> • Large footprint • Significant infrastructure • Water / sewer hookup, fees & permits • High energy use • Long cycle times • Secondary waste stream 	<ul style="list-style-type: none"> • Small footprint (75% less) • Minimal infrastructure • No water/sewer hookup or fees • Lower energy use • Faster cycle time • All waste captured onboard

Source: CO2Nexus Inc.

5.2.1 Beyond Cleanroom Garments

Laundry facilities that service cleanroom apparel is just one outlet for a barrier style textile cleaning system. Hospital and health care environments, such as nursing homes, or any other hygiene controlled environment employ barrier style laundry systems. In any setting where reducing the risk of recontamination and cross contamination of materials is important, a barrier style laundry is appropriate.

The Tersus™ BA model is an ideal platform from which to develop cleaning protocols for other garments and textiles. While the focus of this project was on cleanroom apparel, other applications are possible, including for example bed linens, staff uniforms, lab coats and hospital curtains.

CHAPTER 6:

Next Steps

6.1 Volume Manufacturing

To prepare to commercialize this demonstrated technology, CO2Nexus underwent a full system design evaluation, supply chain analysis and market analysis. A commercialization path was adopted and launched.

Design evaluation concluded updates to the basket drive system, control system and filter system are necessary prior to volume manufacturing. Supply chain modifications were made to ensure all production components and parts are sourced using existing off-the-shelf materials and fabricated using commercially available technologies. All manufacturing, fabrication, and assembly facilities are located at the suppliers or subcontractors current facilities. Those suppliers / facilities have been identified for all primary production areas: pressure vessel fabrication, piping assembly fabrication, support structure fabrication, control system fabrication, component assembly, system & component testing and factory acceptance testing.

A marketing campaign targeting potential end users has been developed and activated. To date CO2Nexus has received positive market feedback from end users (beyond Aramark), as well as numerous inquiries for Tersus™ BA cleanroom solutions. In September 2013, CO2Nexus was named one of five finalists for the prestigious Cleanroom Innovation Award, sponsored and organized annually by Reinraum Akademie (based in Germany) and Cleanroom Magazine. Candidates are selected for groundbreaking advances in innovation, sustainability and efficiency.

An investment threshold between \$500k and 750k is anticipated to commercially launch the Tersus™ BA cleanroom system. An estimated 42-46 weeks are necessary from redesign to market introduction.

6.2 Financial Model

Projected target cost of a Tersus™ cleanroom system producing 100 to 150 lbs throughput per hour is between \$350k and \$400k. There are two models of implementing this system:

- Drop-in replacement at existing water-based cleaning facilities
- New, modular CO₂-only cleaning facility

6.2.1 Drop-In Replacement

A drop-in replacement which costs \$400k, processes 120 lbs garments per hour and affords a 40-50 percent operational savings per pound of garments laundered has an estimated 6.7 – 8 years payback term⁸.

⁸ Assumes 96 hours per week operation.

In the immediate future CO2Nexus endeavors to reduce equipment cost by at least 12 - 15 percent with volume manufacturing. A drop-in replacement which costs \$350k, processes 120 lbs garments per hour and affords a 40-50 percent operational savings per pound of garments laundered has an estimated 6 – 7 years payback term⁹.

6.2.2 New, Modular CO₂ Facility

As discussed in section 5.2 *Impact* an exclusively CO₂-based laundry facility can be established on a small footprint, with minimal infrastructure and lower capital investment compared to a water-based laundry. The below models demonstrate establishing a new CO₂-based laundry versus a new water-based laundry. Both are calculated based on processing 20,000 lbs garments per week – a modest size laundry.

Water-based facilities will be impacted by rising water and utility rates in years to come, which will negatively impact their return on investment (ROI) and payback period. Water prices alone have risen in parts of the United States by 25 percent since 2010¹⁰. These rising utility rates are represented by Future 1 and 2 in *Table 14*.

CO₂-based systems will continue to improve their efficiency and process optimization – an effort water-based systems have spent decades undergoing. CO₂-based capital and operational costs will decrease in years to come – translating to improved ROI and payback figures. Future 1 and 2 in *Table 15* represent forecasted reduction in machine price and improved process efficiency.

Important to note is prices of utilities, labor and other operational costs vary across the United States and the globe. The below economics will be impacted by these geographical variations.

Table 14: Financial Model for New H₂O-Based Cleanroom Laundry

New H ₂ O-based Cleanroom Laundry (based on 20,000 lbs / wk)					
Capital Expenditure		Operational Expenditure (annual)		Payback (yrs)	ROI
Today	\$ 1,415,000	Today	\$ 234,000	4	38%
Future 1	\$ 1,415,000	Future 1	\$ 269,360	4.4	35%
Future 2	\$ 1,415,000	Future 2	\$ 304,200	5	34%

Source: CO2Nexus Inc.

⁹ Assumes 96 hours per week operation.

¹⁰ Circle of Blue, "The Price of Water 2013: Up Nearly 7 Percent in Last Year in 30 Major U.S. Cities; 25 Percent Rise Since 2010", June 05, 2013.

Table 15: Financial Model for New CO₂-Based Cleanroom Laundry

New CO ₂ -based Cleanroom Laundry (based on 20,000 lbs / wk)					
Capital Expenditure		Operational Expenditure (annual)		Payback (yrs)	ROI
Today	\$ 900,000	Today	\$ 115,440	1.9	58%
Future 1	\$ 740,000	Future 1	\$ 86,320	1.5	71%
Future 2	\$ 580,000	Future 2	\$ 57,200	1.1	92%

Source: CO₂Nexus Inc.

CHAPTER 7:

Recommendations

Cleanroom laundries serve a specific customer set with specific garment cleaning requirements. While the greater garment and textile cleaning market is much larger and highly diverse, most players are equally notorious for their vast utility consumption. An estimated 15 billion pounds of commercial textiles are laundered annually in the United States. That translates to roughly 50 billion gallons of potable water used each year. Additional RD&D for the development of new CO₂-based garment and textile cleaning applications is both recommended and encouraged by CO₂Nexus.

Beyond textile cleaning applications, CO₂-based processes have been demonstrated to benefit many industries, such as food, pharmaceuticals, agriculture and textile manufacturing. CO₂Nexus supports the advance of CO₂-based processes which can eliminate water, energy and hazardous chemical use in industrial processes, as well as create novel and sustainable products. CO₂Nexus supports continued RD&D opportunities from federal and state institutions, like the California Energy Commission, that advance these technologies and promote them in the marketplace.

GLOSSARY

Term	Definition
Barrier cleaning	Style of materials cleaning in which dirty materials are strictly separated from clean materials. Separation is usually achieved by secluding clean materials from dirty materials using designated quality controlled environments.
Bioburden	The number of bacteria living on a surface that has not been sterilized.
CO ₂	Carbon dioxide is a naturally occurring chemical compound composed of two oxygen atoms and one carbon atom.
CFU	Colony forming units is the estimate of viable bacterial or fungal numbers.
Electrostatic Discharge	The sudden flow of electricity between two electrically charged objects caused by contact.
HEPA	High-efficiency particulate absorption is a type of air filter.
Particulates	In the context of this project, particulates (or particles) are any pieces of solid or liquid matter present on garments.
Process optimization	The method of modifying process parameters to achieve improved equipment or process performance.
SOP	Standard operating procedure is a detailed, written instruction to achieve uniformity in the performance of a specific function.
Tersus™ BA	Trademarked name of CO2Nexus' barrier style cleaning systems.
Validation	In the context of this project, the process by which it is confirmed that a product or service meets the needs of its users.